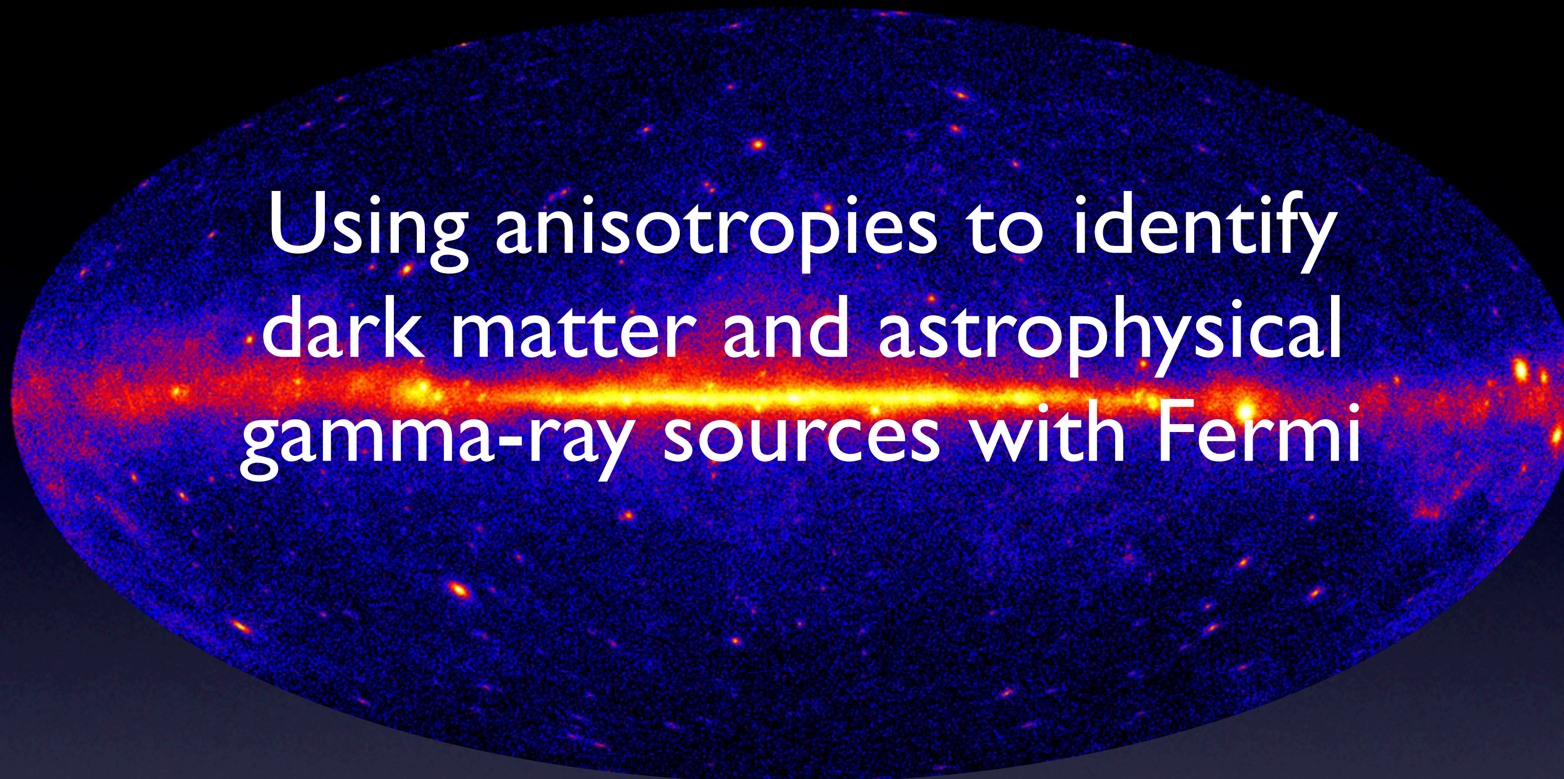
Image Credit: NASA/DOE/International LAT Team



Using anisotropies to identify dark matter and astrophysical gamma-ray sources with Fermi

Jennifer Siegal-Gaskins

CCAPP, Ohio State University

with
Brandon Hensley (Caltech)
Vasiliki Pavlidou (Caltech)
Rebecca Reesman (OSU)
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Terry Walker (OSU)

based on
JSG, JCAP, 10, 040 (2008)
JSG & Pavlidou, PRL, 102, 241301 (2009)
Hensley, JSG, & Pavlidou, arXiv:0912.1854
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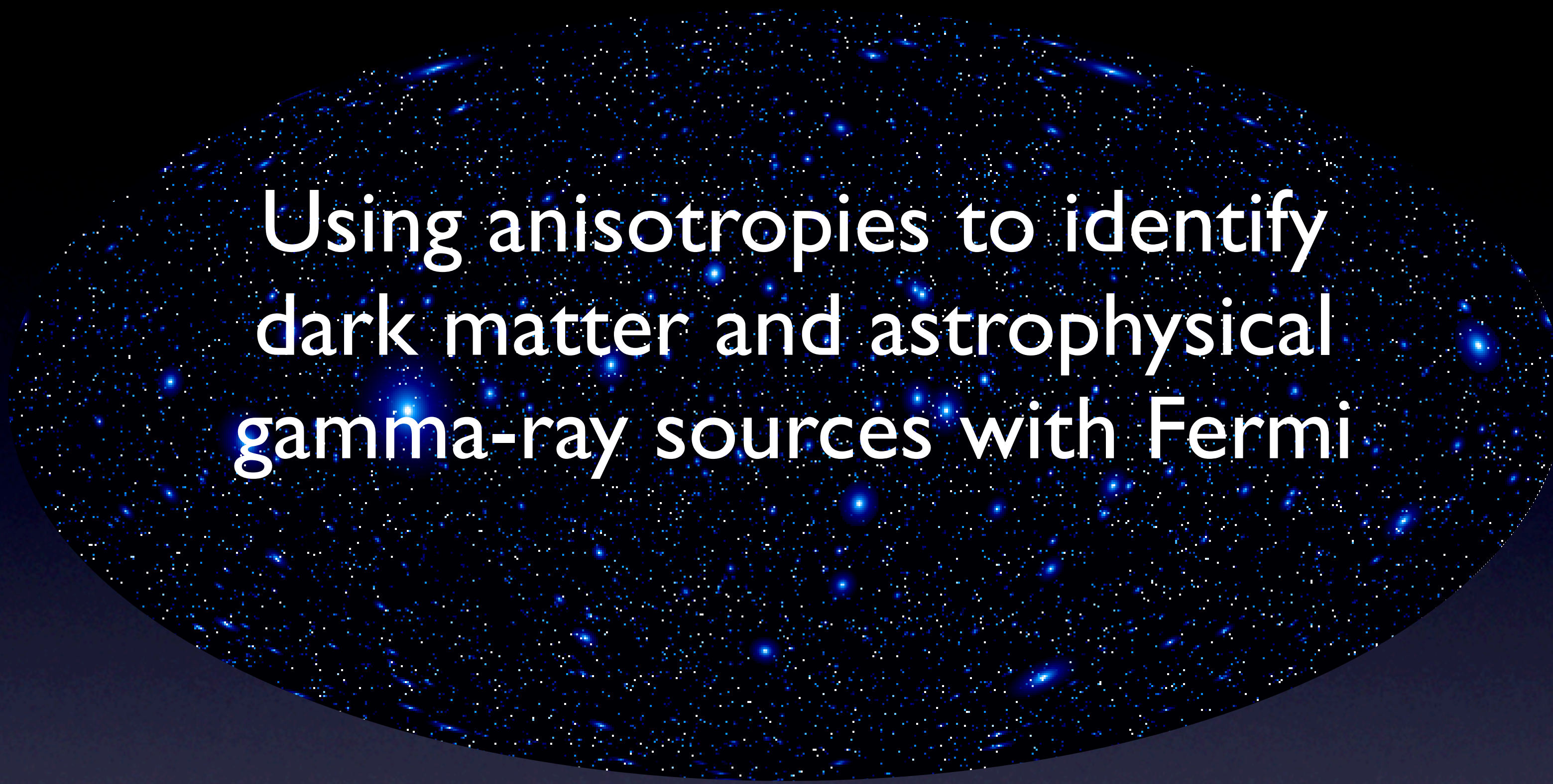
Pavlidou, Reesman, JSG, Profumo, & Walker, in prep



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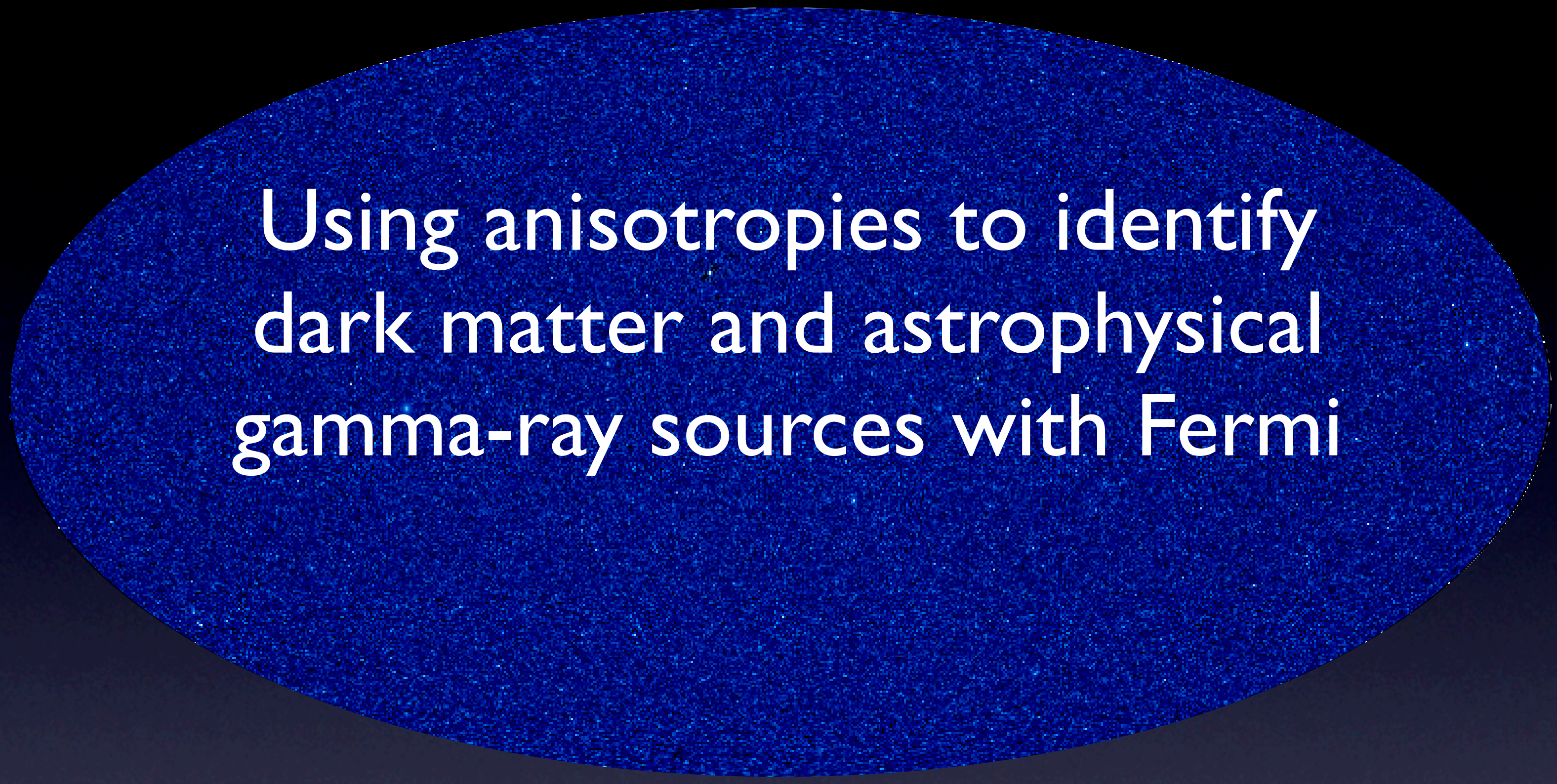

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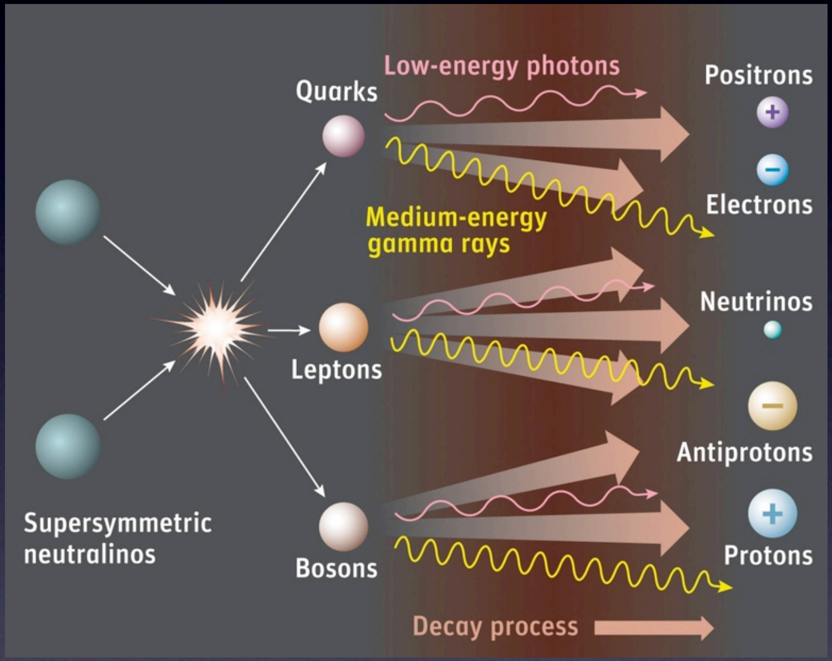
Searching for dark matter in diffuse gamma-ray emission

- annihilation of dark matter particles produces gamma-rays which could be detected by Fermi



Credit: Sky & Telescope / Gregg Dinderman

Searching for dark matter in diffuse gamma-ray emission

- annihilation of dark matter particles produces gamma-rays which could be detected by Fermi
- cold dark matter models predict structure down to very small scales, including an abundance of substructure in the halo of the Galaxy

Springel et al. (Virgo Consortium)

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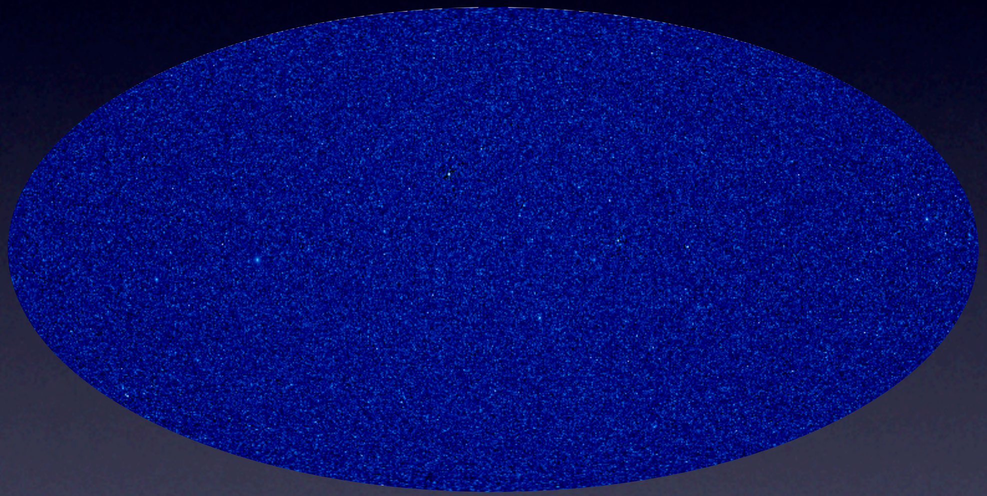

JSG 2008

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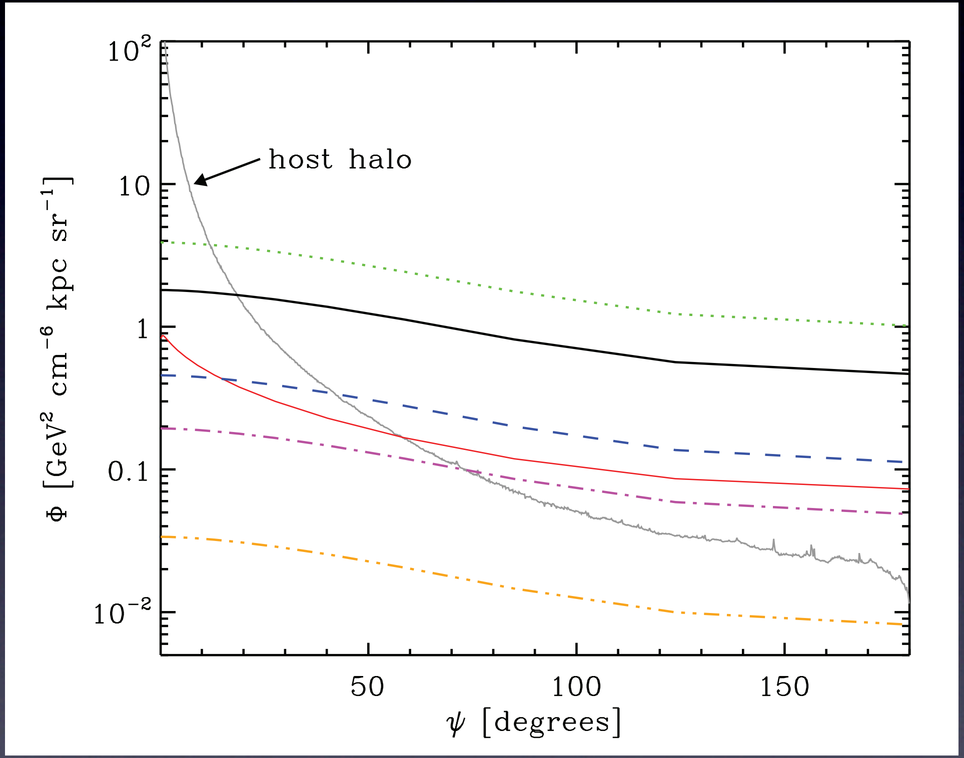
Galactic DM annihilation flux



Kuhlen, Diemand, & Madau 2008

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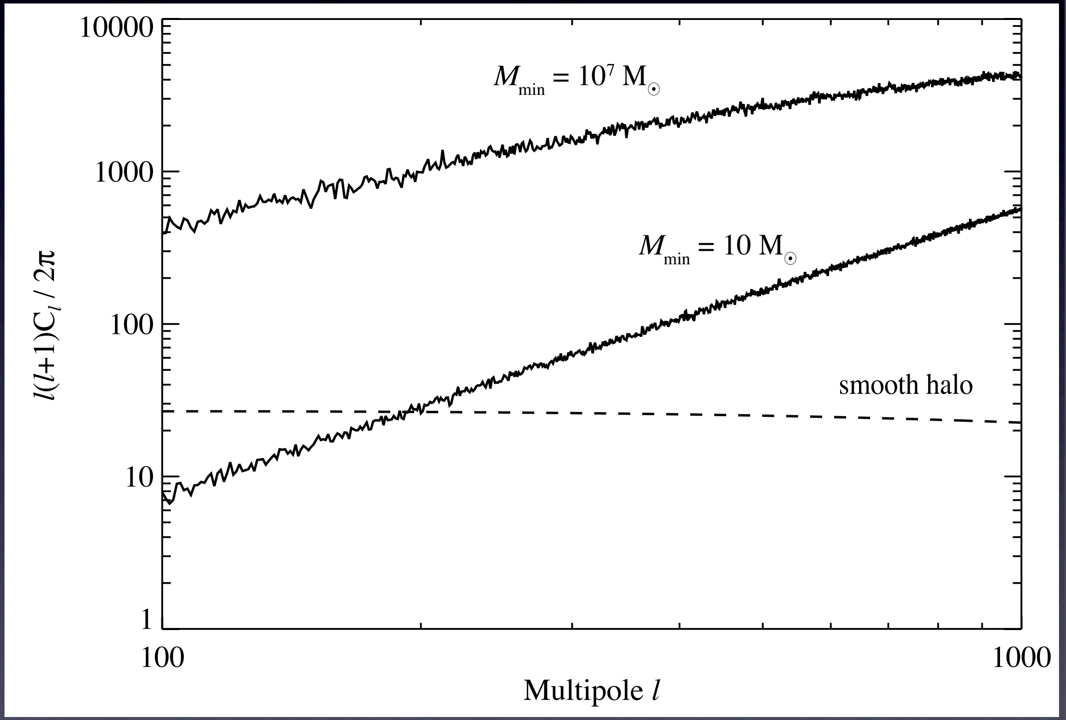

JSG 2008

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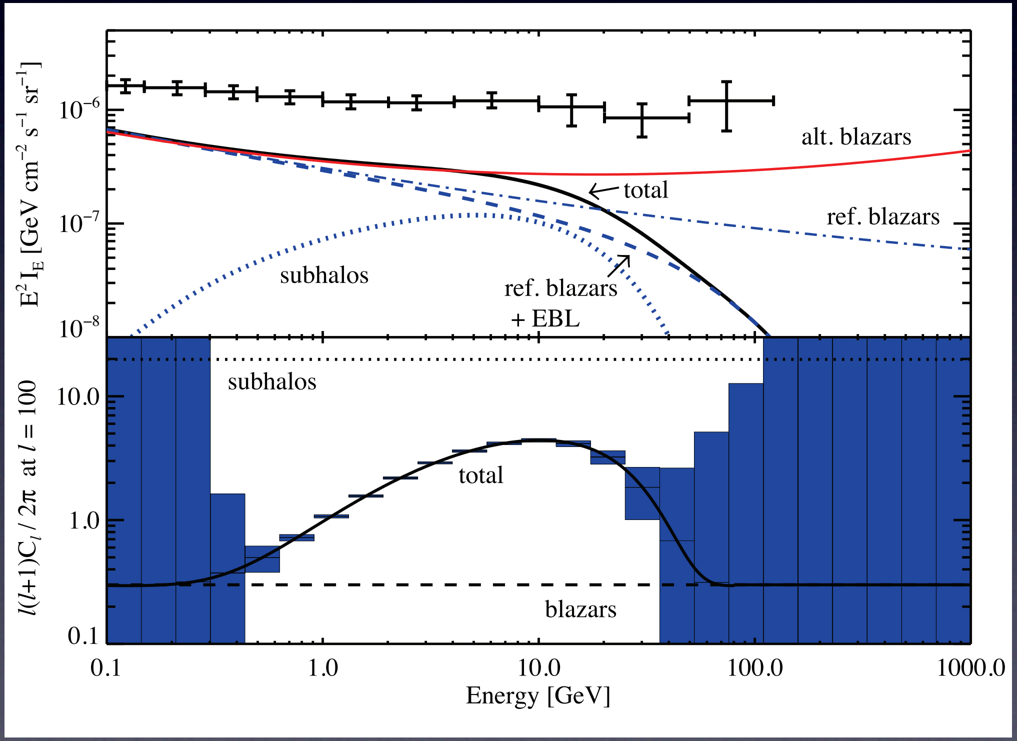
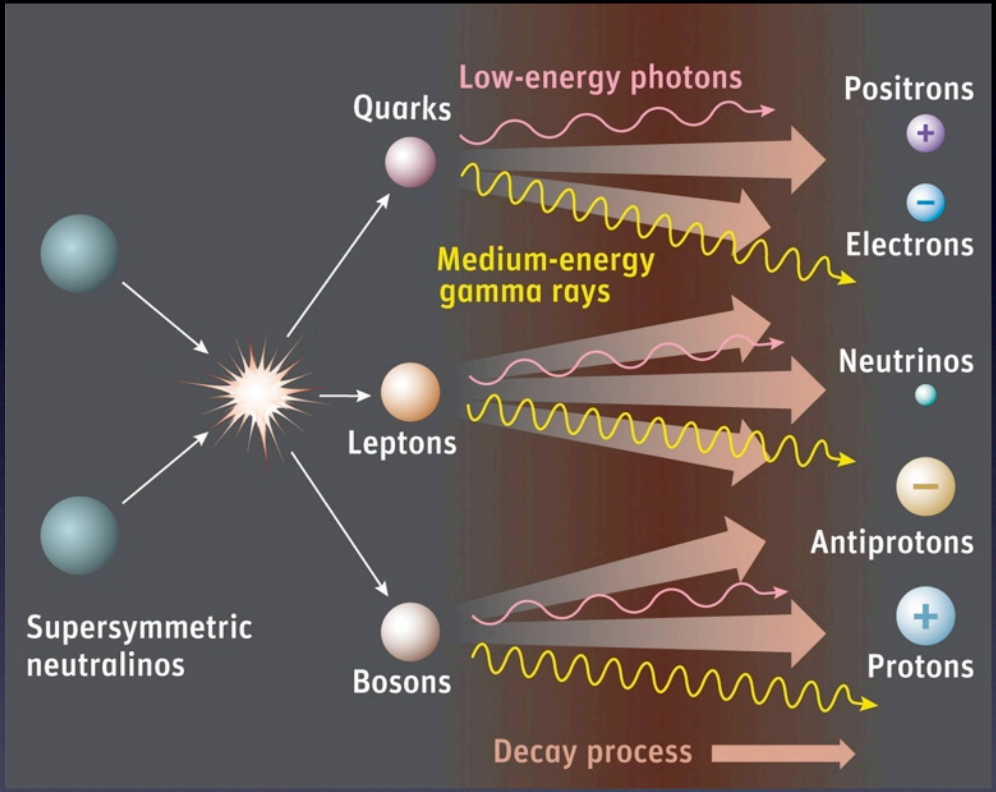
- characteristic fluctuations in the intensity of the diffuse emission on small angular scales (anisotropies) could be used to disentangle a dark matter signal
- combining anisotropies with energy information allows for a robust detection, significantly extends the sensitivity of current gamma-ray experiments, and may enable the properties of the dark matter particle to be extracted
- anisotropy analysis could be a powerful tool for identifying contributions to the diffuse from astrophysical source classes and constraining their properties



JSG & Pavlidou 2009

The dark matter annihilation signal

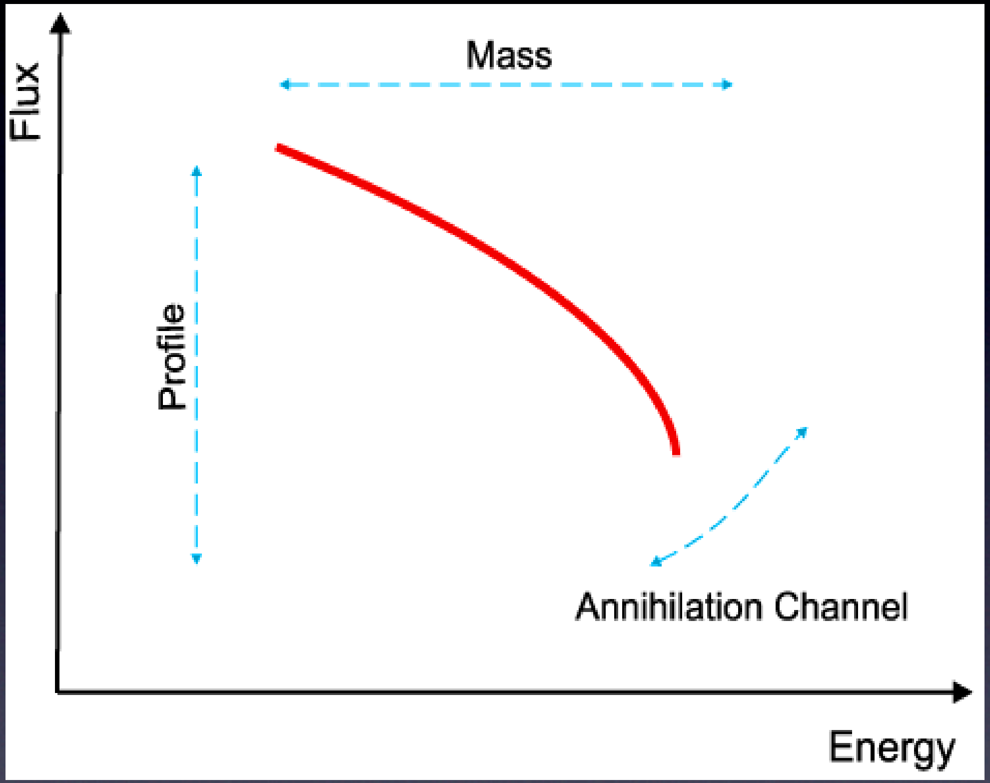
- annihilation of dark matter can produce a variety of potentially detectable particles
- gamma-rays and neutrinos point back to source, can map dark matter distribution



Credit: Sky & Telescope / Gregg Dinderman

The dark matter annihilation signal

- annihilation of dark matter can produce a variety of potentially detectable particles
- gamma-rays and neutrinos point back to source, can map dark matter distribution
- spectrum of annihilation products encodes info about intrinsic particle properties
- variation in the intensity of the signal along different lines of sight is determined exclusively by the distribution of dark matter



Bertone 2007

$$I(\psi) = \frac{K}{4\pi} \int_{los} \mathrm{d}s \; \rho^2(s, \psi) \qquad K = \frac{N_\gamma \langle \sigma v \rangle}{2 m_\chi^2}$$

The Fermi Gamma-ray Space Telescope

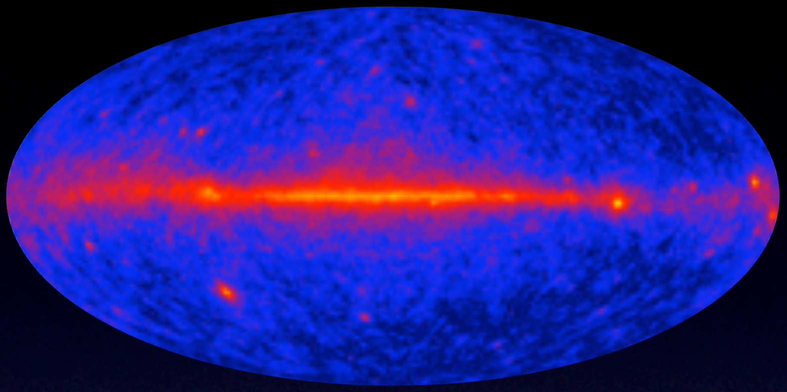
- satellite
- energy range: 100 MeV to a few hundred GeV
- effective area ~ 10^4 cm^2 (size-limited detector!)
- angular resolution ~ 0.1 deg above 10 GeV
- FOV ~ 2.4 sr
- primarily observes in sky-scanning mode; ~24 hr per day livetime
- excellent charged particle background rejection

Credit: NASA/General Dynamics

What is making the large-scale isotropic diffuse emission?

- many astrophysical sources are *guaranteed* to contribute to the diffuse emission, e.g.:
  - blazars
  - star-forming galaxies
  - millisecond pulsars
- unknown/unconfirmed source classes could also contribute:
  - dark matter
  - ???

the diffuse emission contains a great deal of information about the contributors!



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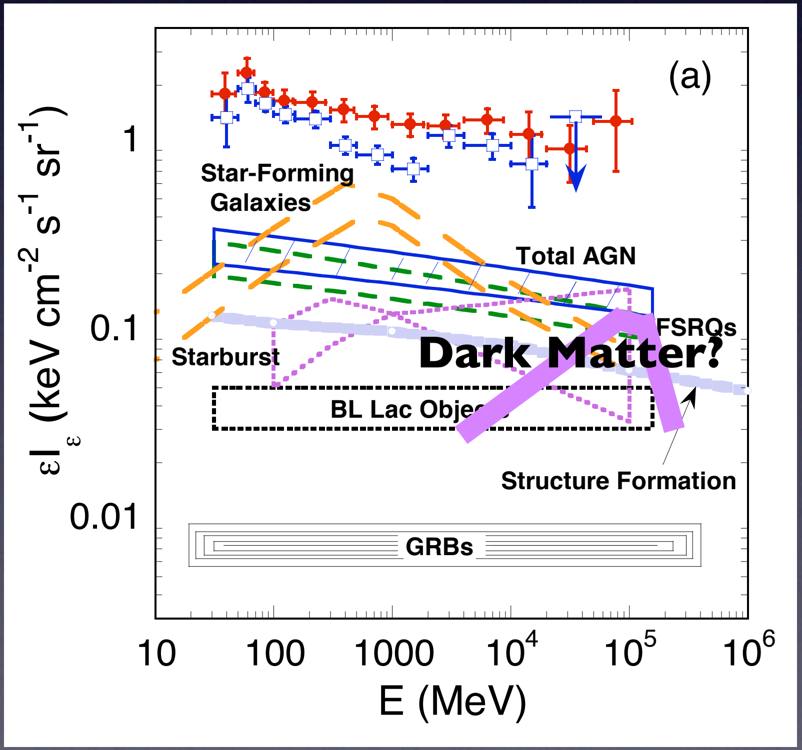


Dermer 2007

Using anisotropy to find unresolved source populations

- the angular power spectrum: characterizes intensity fluctuations as a function of angular scale

$$C_\ell \text{ vs. } \ell$$

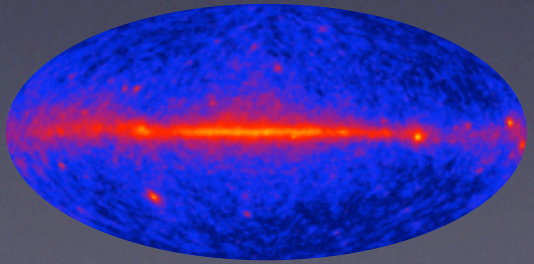
- the intensity energy spectrum: intensity as a function of energy

$$I \text{ vs. } E$$

- the anisotropy energy spectrum: characterizes intensity fluctuations at a *fixed* angular scale as a function of energy

$$C_\ell \text{ vs. } E$$
$$(\text{at a fixed } \ell)$$

- large-scale angular distribution: tests whether emission is correlated with Galactic structures



Credit: NASA/DOE/International LAT Team

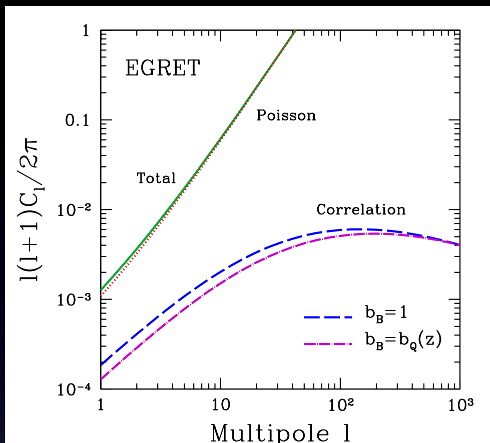
Characterizing the anisotropy

- for these source classes, we use the angular power spectrum of intensity fluctuations in units of mean intensity (dimensionless)

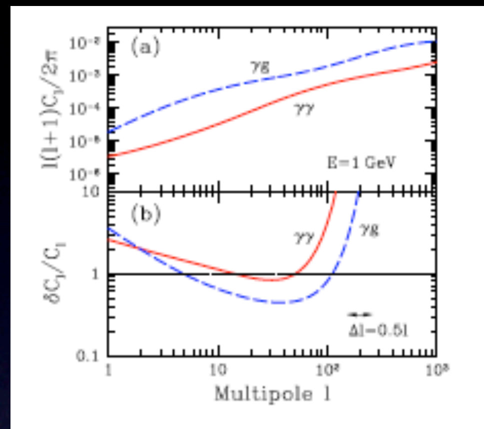
$$\delta I(\psi) \equiv \frac{I(\psi) - \langle I \rangle}{\langle I \rangle} \Rightarrow \delta I(\psi) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\psi) \Rightarrow C_\ell = \langle\, |a_{\ell m}|^2 \rangle$$

- fluctuation power spectra are *independent of intensity normalization*
  - shape of the angular power spectrum is determined *exclusively* by the source distribution ↔ independent of uncertainties in the intensity or energy spectrum of the signal (e.g., unknown properties of the dark matter particle)
  - avoids common difficulty of extracting a signal of uncertain amplitude and spectrum from uncertain foregrounds
  - avoids different amplitude angular power spectra in different energy bins
- new diagnostic (no constraints yet), can be combined with position, energy spectrum, etc for stronger constraints
- related anisotropy probe: 1-pt flux PDF could be used to test for dark matter signal (Lee et al. 2009, Dodelson et al. 2009)

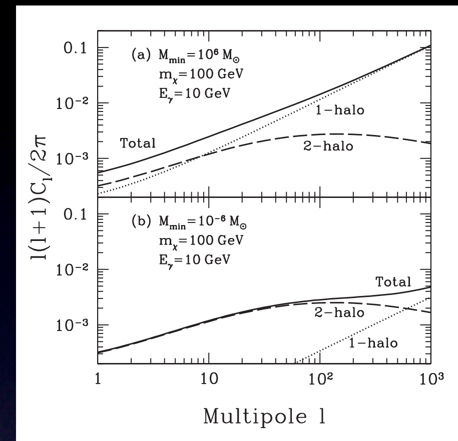
Angular power spectra of unresolved gamma-ray populations



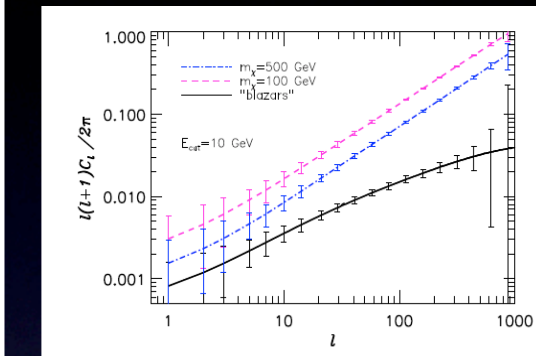
Blazars
Ando, Komatsu, Narumoto & Totani 2007



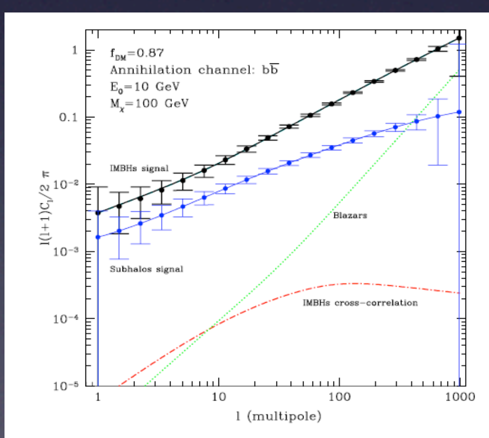
Starforming Galaxies
Ando & Pavlidou 2009



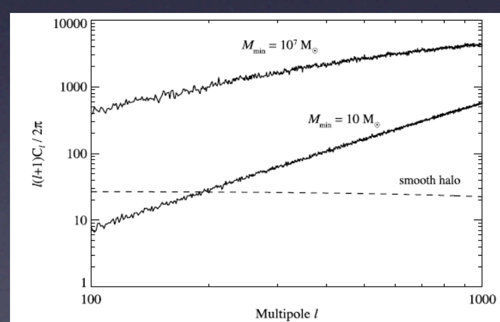
Extragalactic DM
Ando & Komatsu 2006



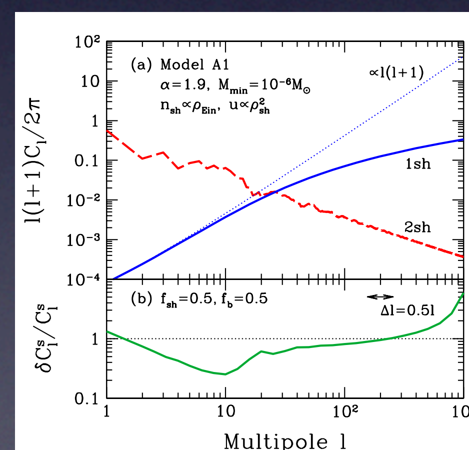
Extragalactic DM
Cuoco et al 2008



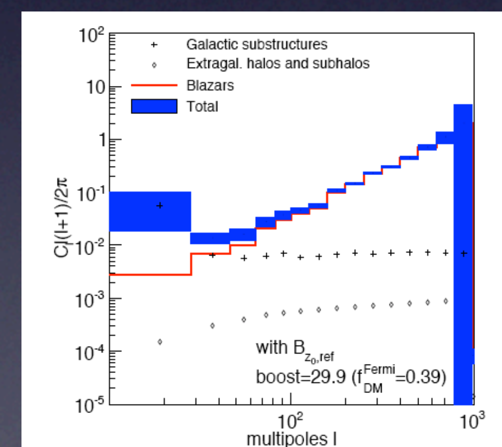
DM around EG IMBHs
Taoso, Ando, Bertone & Profumo 2008



Galactic subhalos
JSG 2008



Galactic subhalos
Ando 2009



Galactic and EG subhalos
Fornasa, Pieri, Bertone & Branchini 2009

How to identify source populations with anisotropy?

- the angular power spectrum of the total emission is determined by

    1. the fractional contributions of each source class to the intensity
    2. the amplitude of their individual angular power spectra

$$C_\ell^{\rm tot} = f_{\rm EG}^2 C_\ell^{\rm EG} + f_{\rm DM}^2 C_\ell^{\rm DM} + \cancel{2 f_{\rm EG} f_{\rm DM} C_\ell^{\rm EG\times DM}}$$

- most gamma-ray source classes are effectively uncorrelated (i.e., cross-correlation term is negligible)

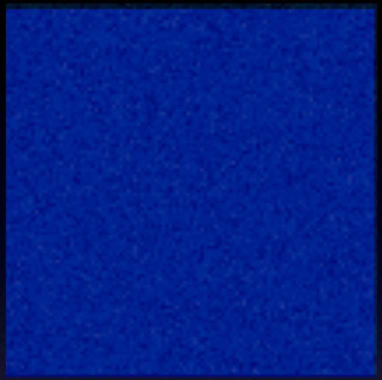
- most gamma-ray source populations produce similarly-shaped, relatively featureless angular power spectra (shot-noise--like), the total angular power spectrum is likely to look shot-noise--like

- intensity and angular power spectrum (especially amplitude) of each individual source class is uncertain (and may not be independent!)

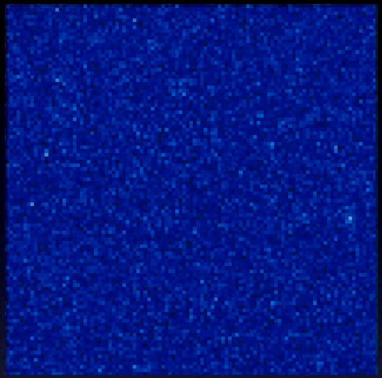
- how can we break the degeneracy to know which sources are making the total measured anisotropy?

examine the energy dependence!

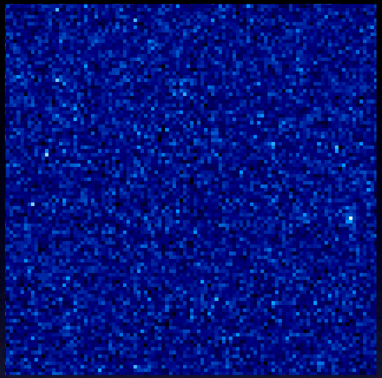
Energy-dependent anisotropy



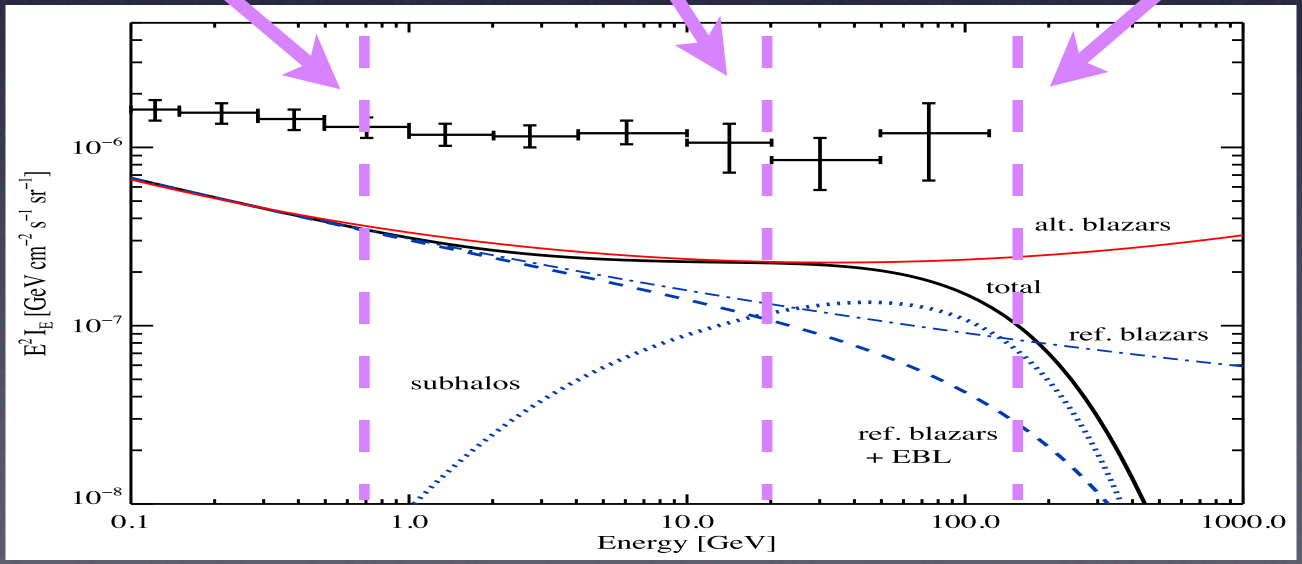
blazars



blazars + dark matter



dark matter



JSG & Pavlidou 2009

The anisotropy energy spectrum

- 'the anisotropy energy spectrum' = the angular power spectrum of the total measured emission at a fixed angular scale (multipole) as a function of energy:

$$C_\ell^{\mathrm{tot}}(E) = f_\mathrm{A}^2(E) C_\ell^\mathrm{A} + f_\mathrm{B}^2(E) C_\ell^\mathrm{B} + \cancel{2 f_\mathrm{A}(E) f_\mathrm{B}(E) C_\ell^{\mathrm{A}\times\mathrm{B}}}$$

- the anisotropy energy spectrum of a SINGLE source population is flat in energy as long as the angular distribution (and hence angular power spectrum) of the emission from a single source population is independent of energy

- how does the anisotropy energy spectrum help?
  - exploits the different energy dependences of the contributions of Galactic dark matter and extragalactic source classes to the total measured emission
  - a transition in energy from an angular power spectrum dominated by the EGRB and one dominated by Galactic dark matter will show up as a modulation in the anisotropy energy spectrum

- this is a generally applicable method for identifying and understanding the properties of contributing source populations (NOT just for dark matter!)

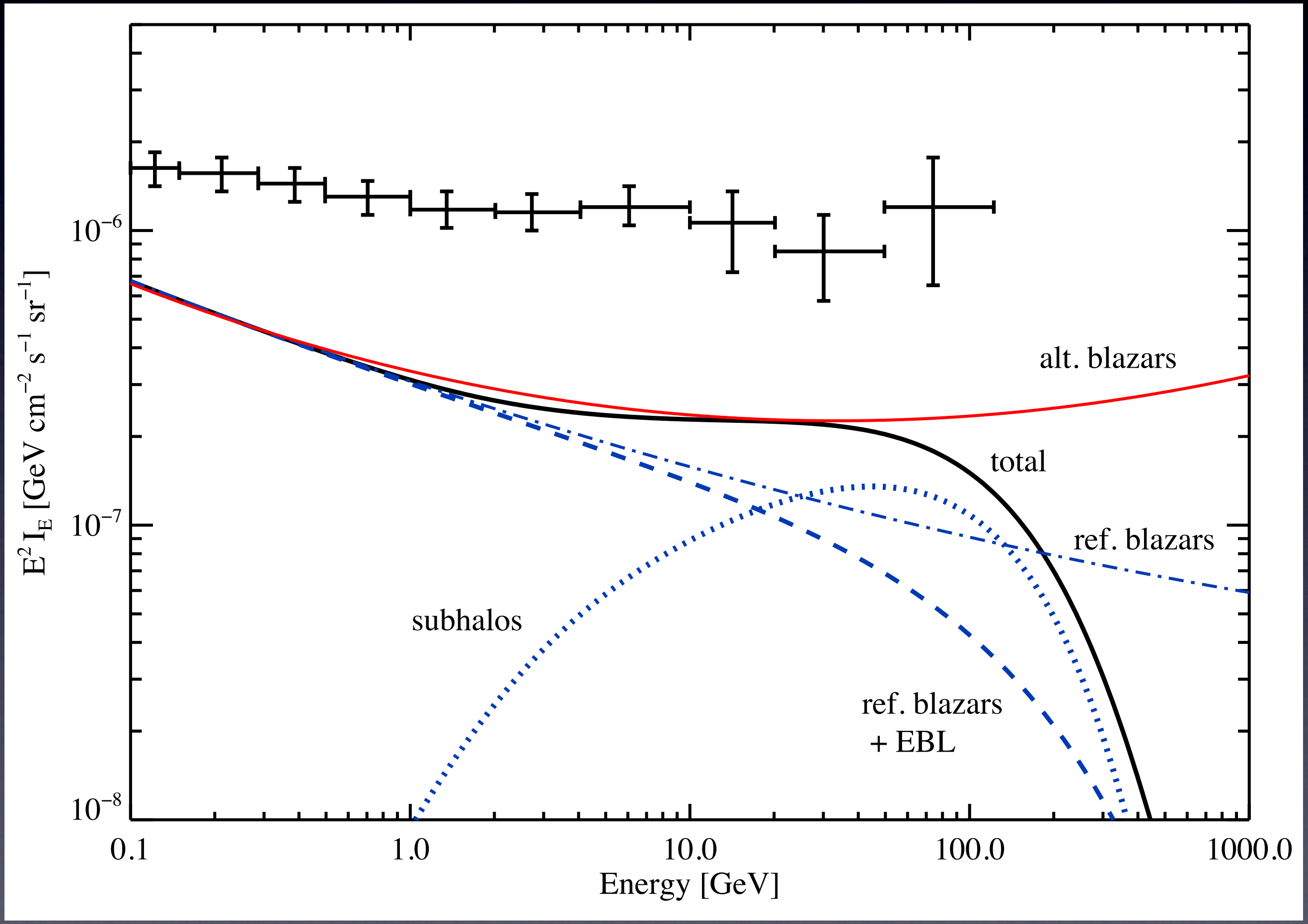
The intensity energy spectrum
(or why we need anisotropy too)

what makes up the "total" measured emission?

#1: ref. blazar model w/ DM
#2: alt. blazar model w/o DM
intensity spectra are degenerate!

- interactions with the extragalactic background light (EBL) may attenuate extragalactic gamma-rays above ~ 10 GeV
- EBL attenuation produces an exponential cutoff in the observed spectrum
- observed blazar spectrum could hide a DM feature!

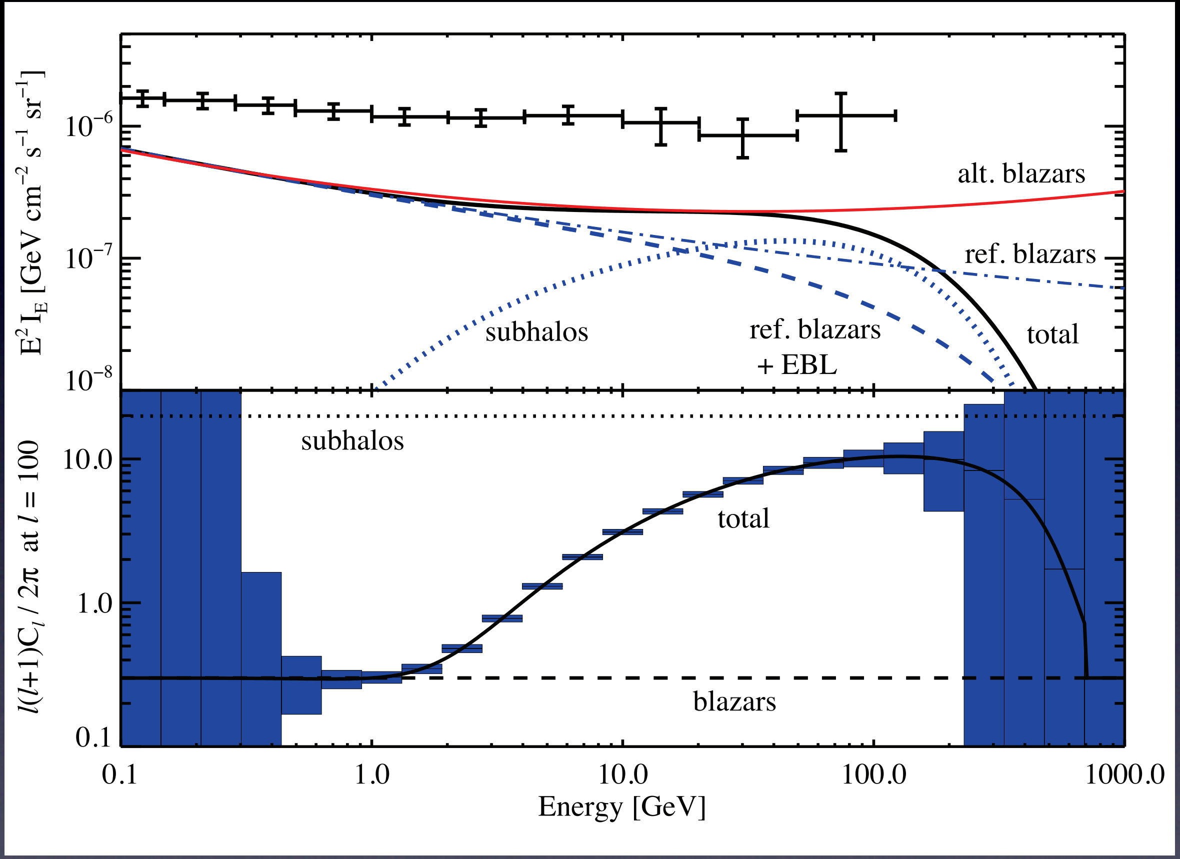
example isotropic diffuse intensity spectrum



JSG & Pavlidou 2009

The anisotropy energy spectrum at work

neutralino mass = 700 GeV



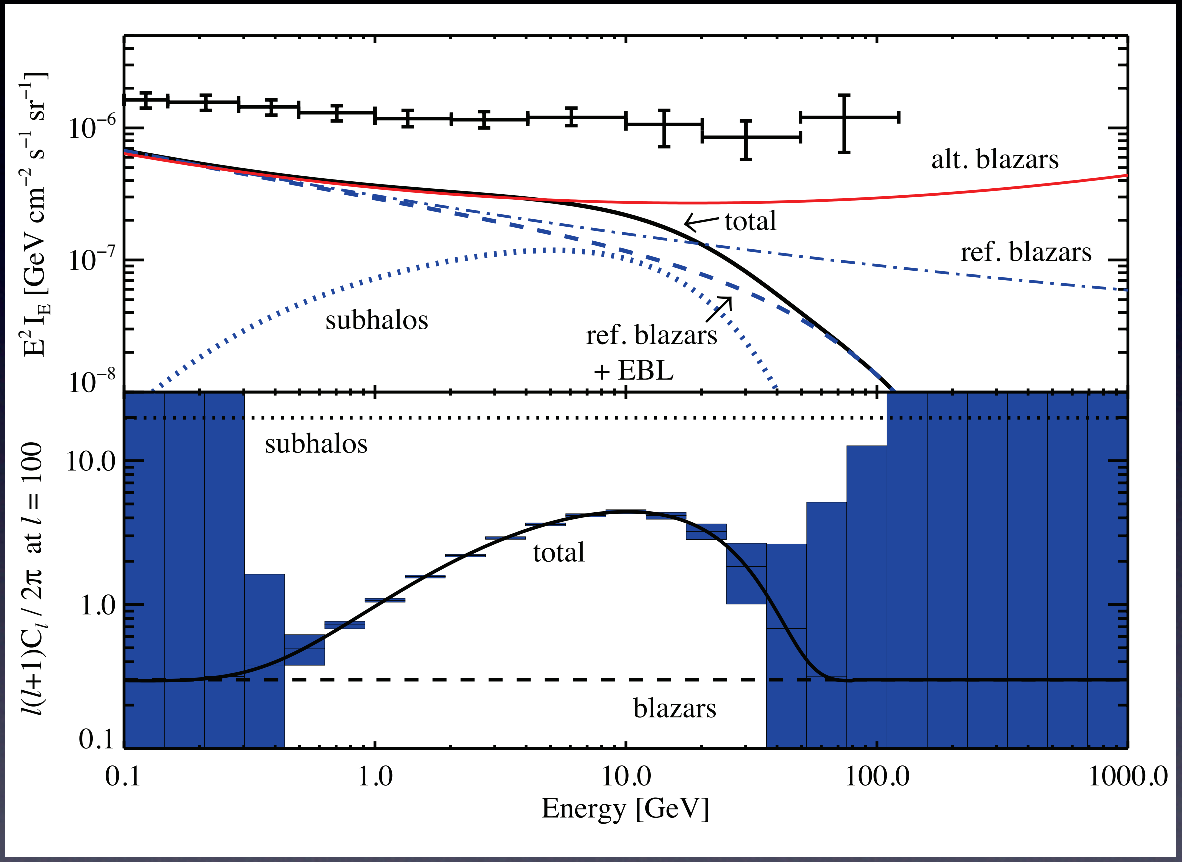
JSG & Pavlidou 2009

- 1-sigma errors
  - 5 years of Fermi all-sky observation
  - 75% of the sky usable
  - N_b/N_s =10 !!!!
- error bars blow up at low energies due to angular resolution, at high energies due to lack of photons

- Galactic dark matter dominates the intensity above ~20 GeV, but spectral cut-off is consistent with EBL attenuation of blazars
- modulation of anisotropy energy spectrum is easily detected!

The anisotropy energy spectrum at work

neutralino mass = 80 GeV



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  - 5 years of Fermi all-sky observation
  - 75% of the sky usable
  - N_b/N_s =10 !!!!
- error bars blow up at low energies due to angular resolution, at high energies due to lack of photons

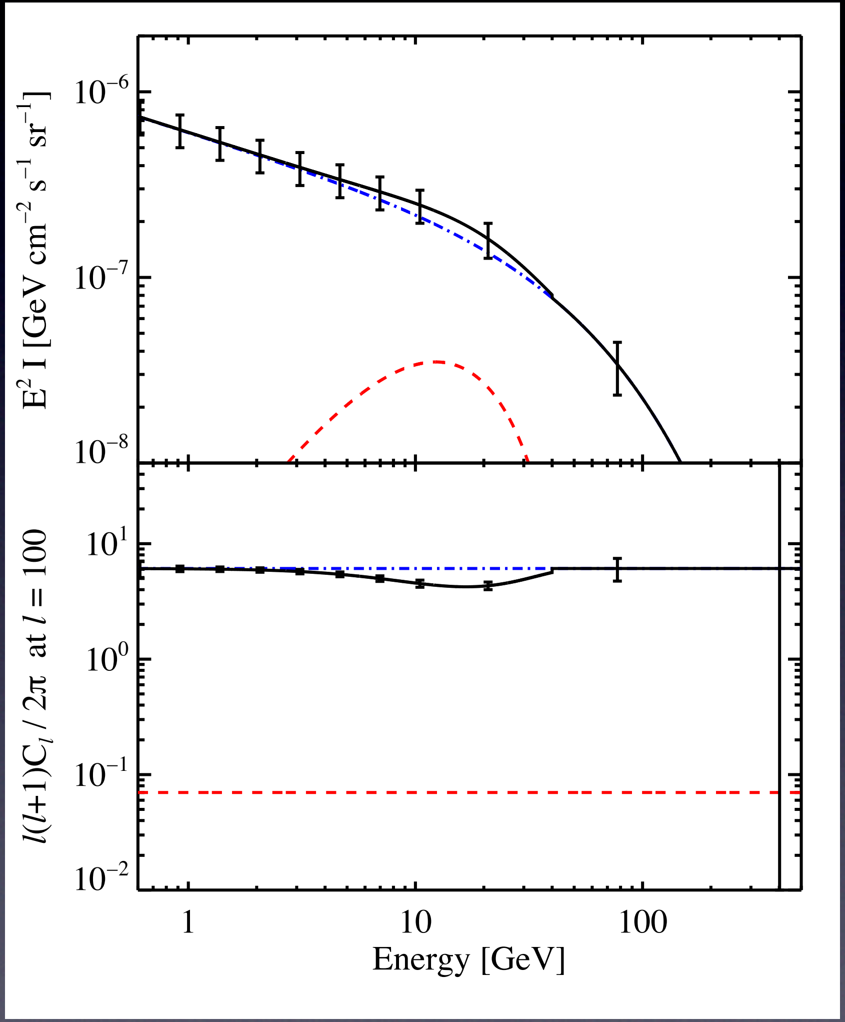
- Galactic dark matter never dominates the intensity and spectral cut-off is consistent with EBL attenuation of blazars
- modulation of anisotropy energy spectrum is still strong!

A simple test to find multiple populations

- we assume the large-scale isotropic diffuse (IGRB) is composed primarily of emission from blazars and dark matter
- we fix the anisotropy properties of both populations, fix the blazar emission to a reference model, and vary the dark matter model parameters (mass, cross-section, annihilation channel)
- we define a simple, 'model-independent' test criterion:

  is the anisotropy energy spectrum at E ≥ 0.5 GeV consistent with a constant value, equal to the weighted average of all energy bins?

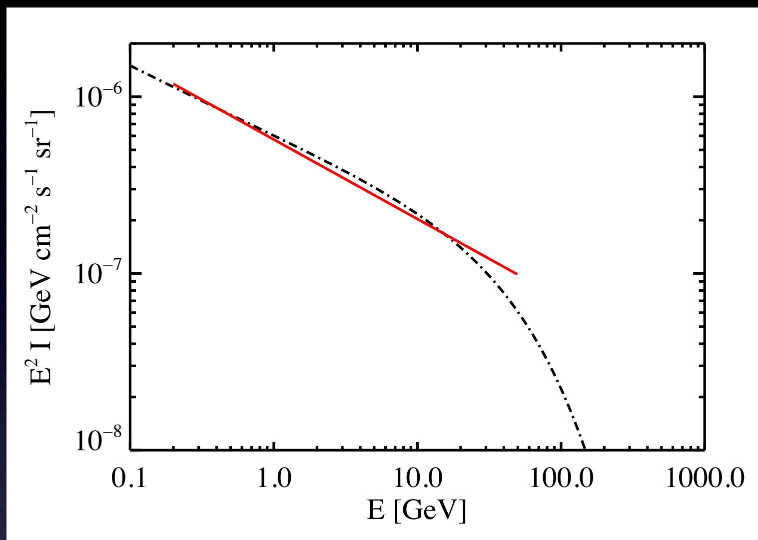
- dark matter model is considered detectable if this hypothesis is rejected by a χ^2 test at the 3-σ level
- NB: this test is not optimized to find specific dark matter models; tailored likelihood analysis could significantly improve sensitivity!



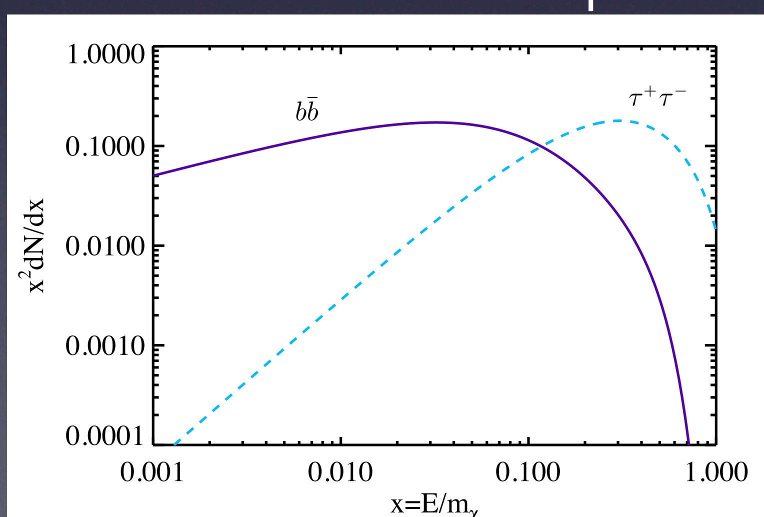
Hensley, JSG, & Pavlidou (2009)

Blazar and dark matter intensity spectra

reference blazar intensity spectrum

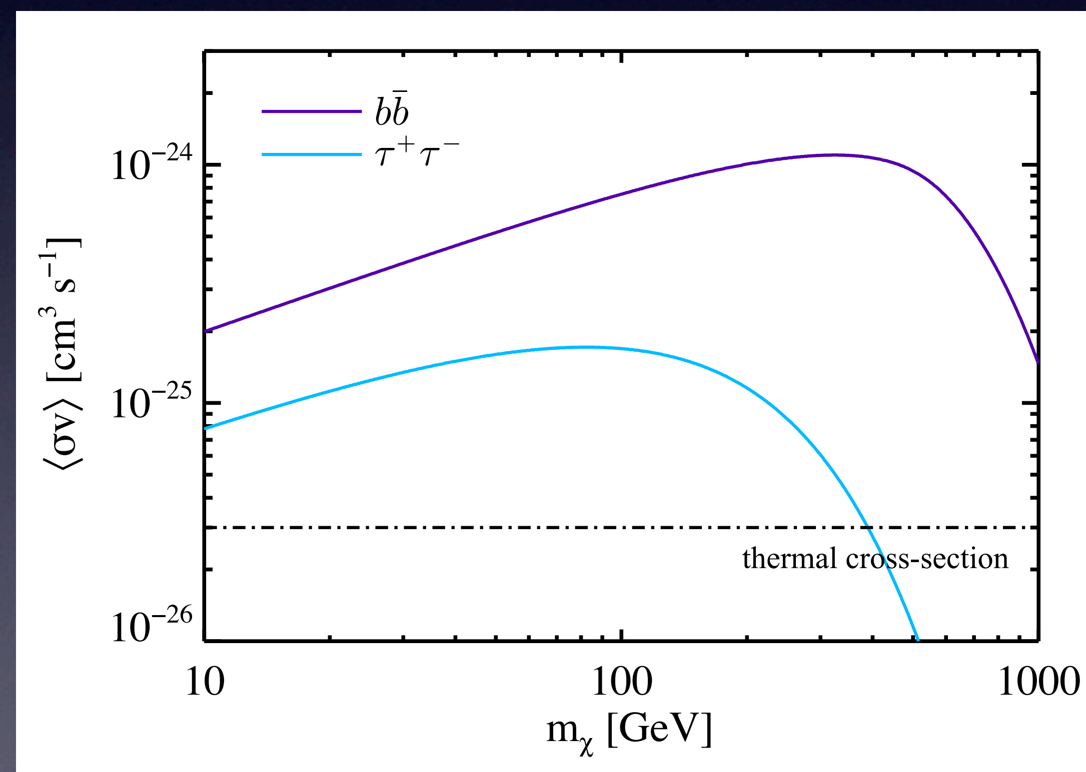


dark matter annihilation spectra



dark matter intensity is subdominant relative to blazar intensity for a large region of dark matter parameter space

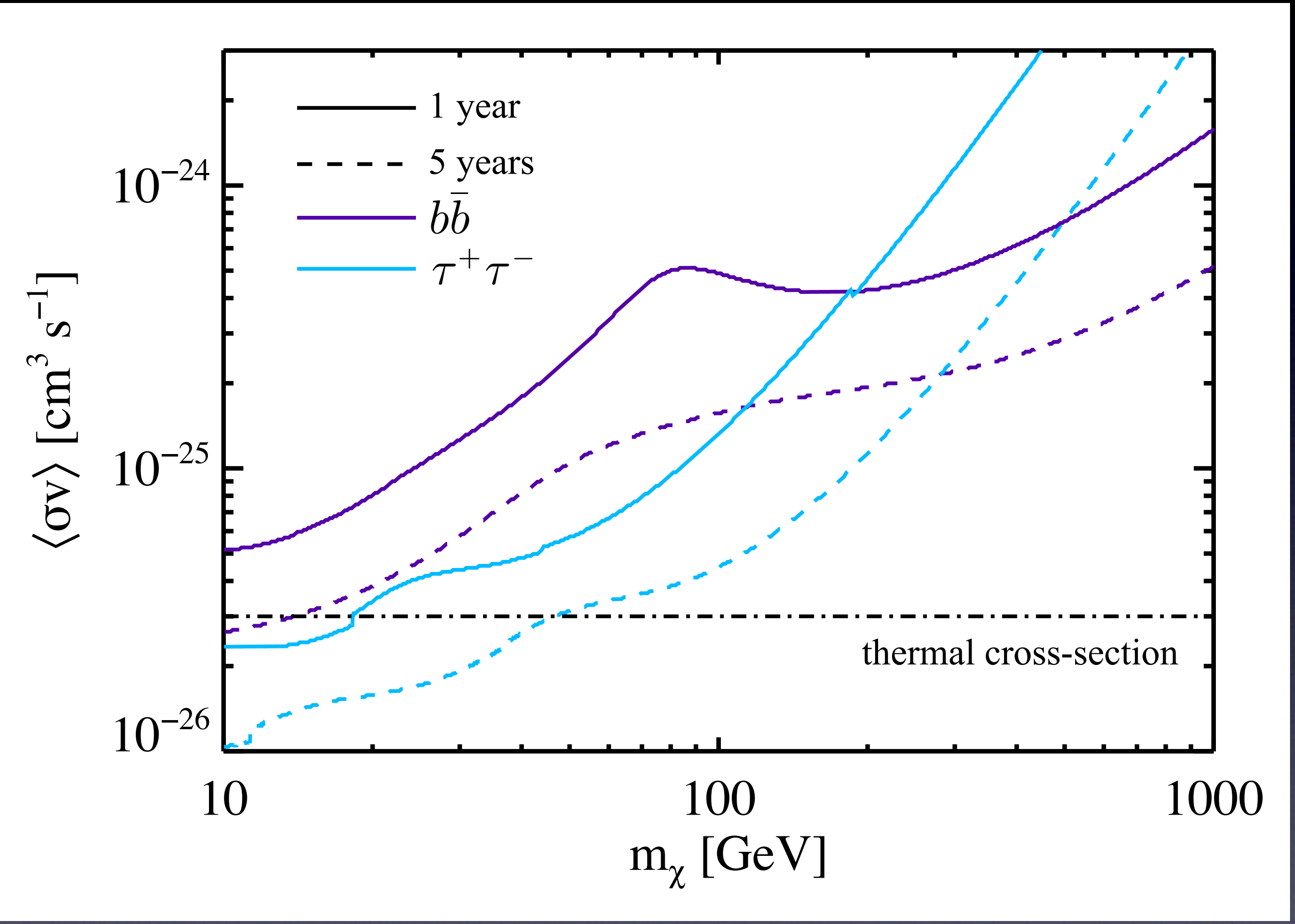
annihilation cross-section below which dark matter is subdominant in intensity at all E > 0.5 GeV



Hensley, JSG, & Pavlidou (2009)

Sensitivity of the anisotropy energy spectrum

- DM produces a detectable feature in the anisotropy energy spectrum for a substantial region of parameter space in this scenario
- technique could probe cross-sections close to thermal; extends the reach of current indirect searches
- NB: this test is highly sensitive to choice of test parameters (multipole, energy binning) and assumed dark matter and blazar angular power spectra amplitudes!

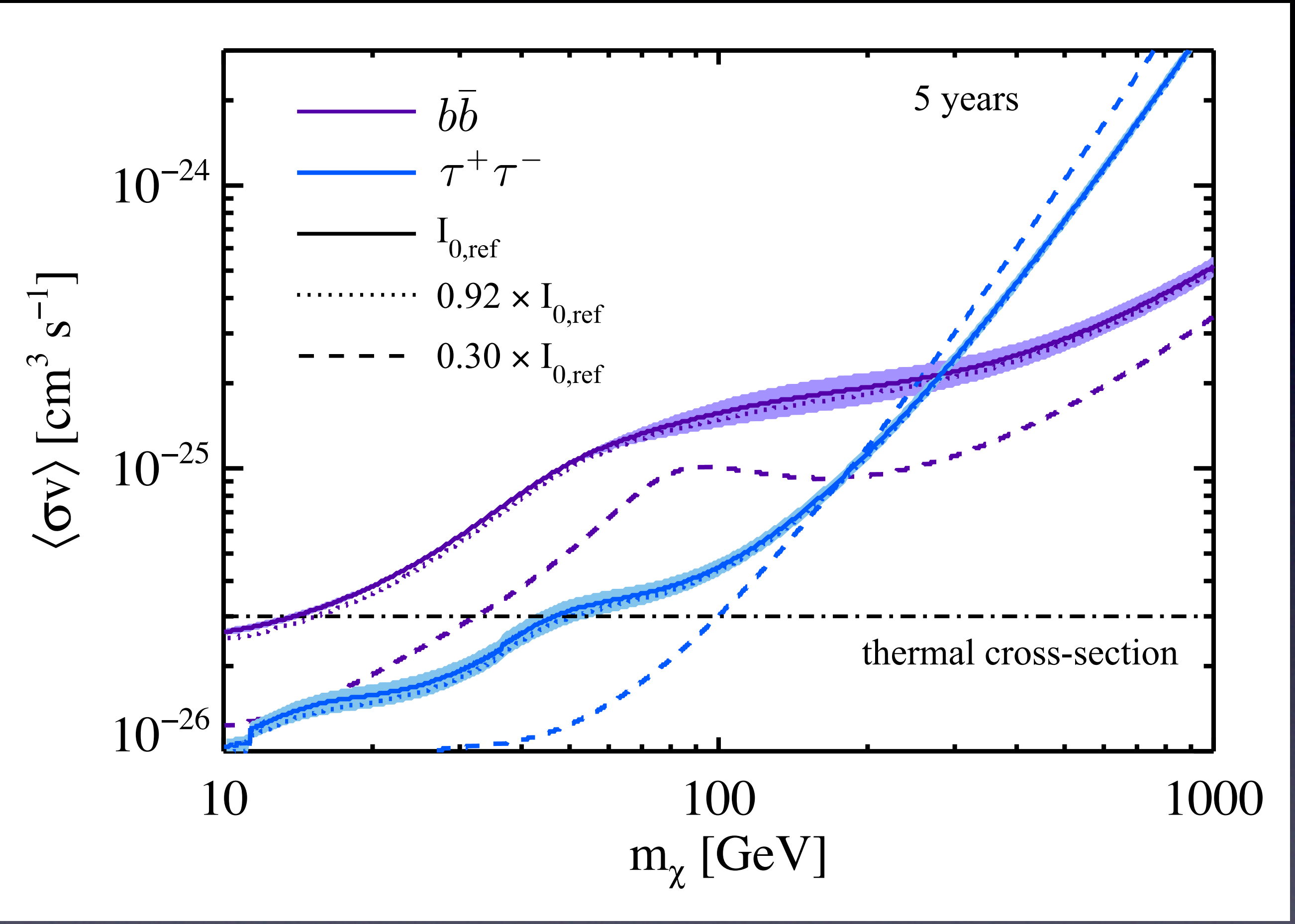


Hensley, JSG, & Pavlidou (2009)

dark matter models above the curves are detectable by this test!

Dependence on blazar model parameters

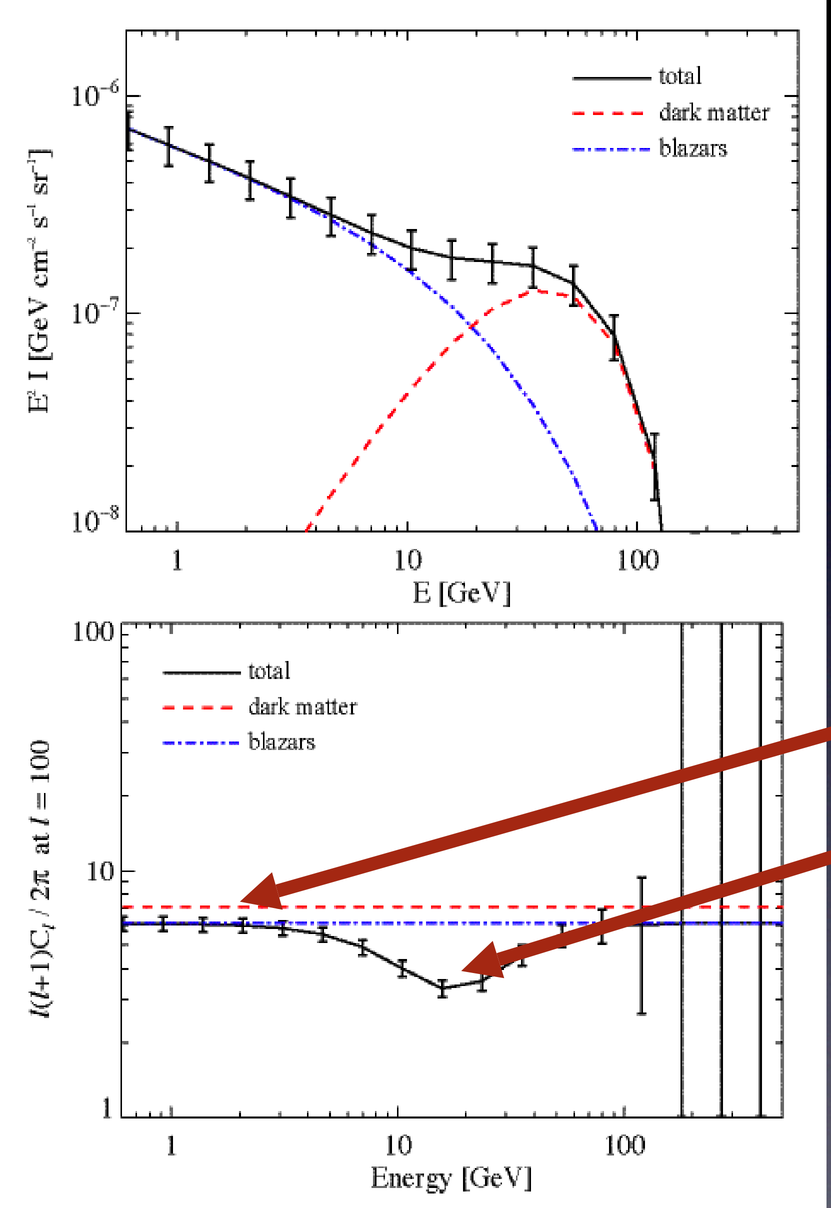
- shaded bands represent uncertainty from varying blazar spectral params within 1-sigma of their max likelihood values
- uncertainty in blazar spectrum impacts test sensitivity negligibly
- reducing blazar normalization increases DM detectability (but two-component scenario less plausible for small blazar normalizations)



Hensley, JSG, & Pavlidou (2009)

dark matter models above the curves are detectable by this test!

Deconvolving the intensity spectra



Hensley, Pavlidou & JSG (in prep)

in a two-component scenario with one component dominating the anisotropy at low energies,

when a dip or plateau in the anisotropy energy spectrum is observed,

each component's intensity spectrum can be deconvolved *without* a priori *assumptions about the shape of the intensity spectra or anisotropy properties!*

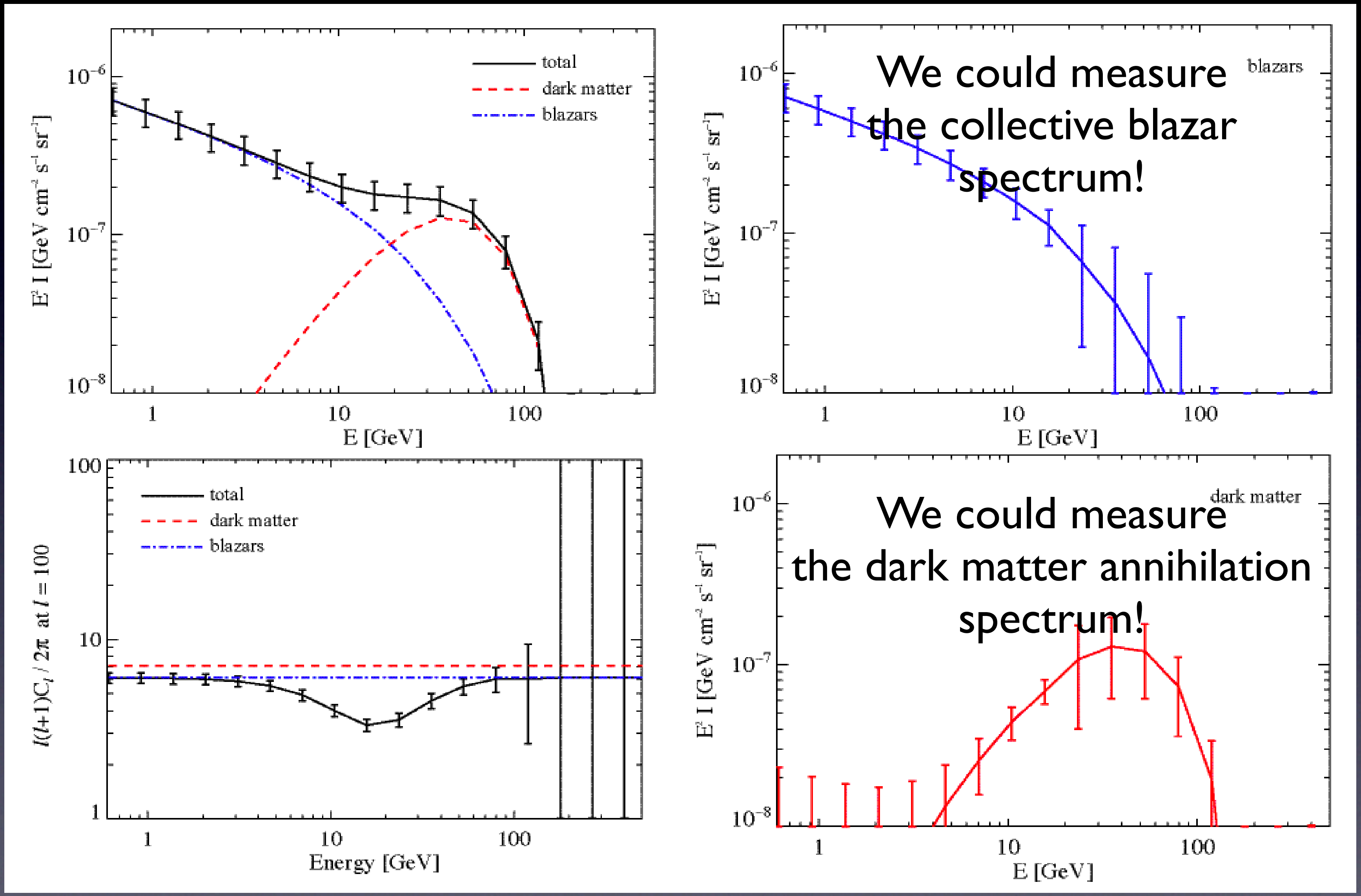
$$C_\ell^{\rm tot} = f_{\rm EG}^2 C_\ell^{\rm EG} + f_{\rm DM}^2 C_\ell^{\rm DM}$$

$$f_{EG} + f_{DM} = 1$$

At minimum:

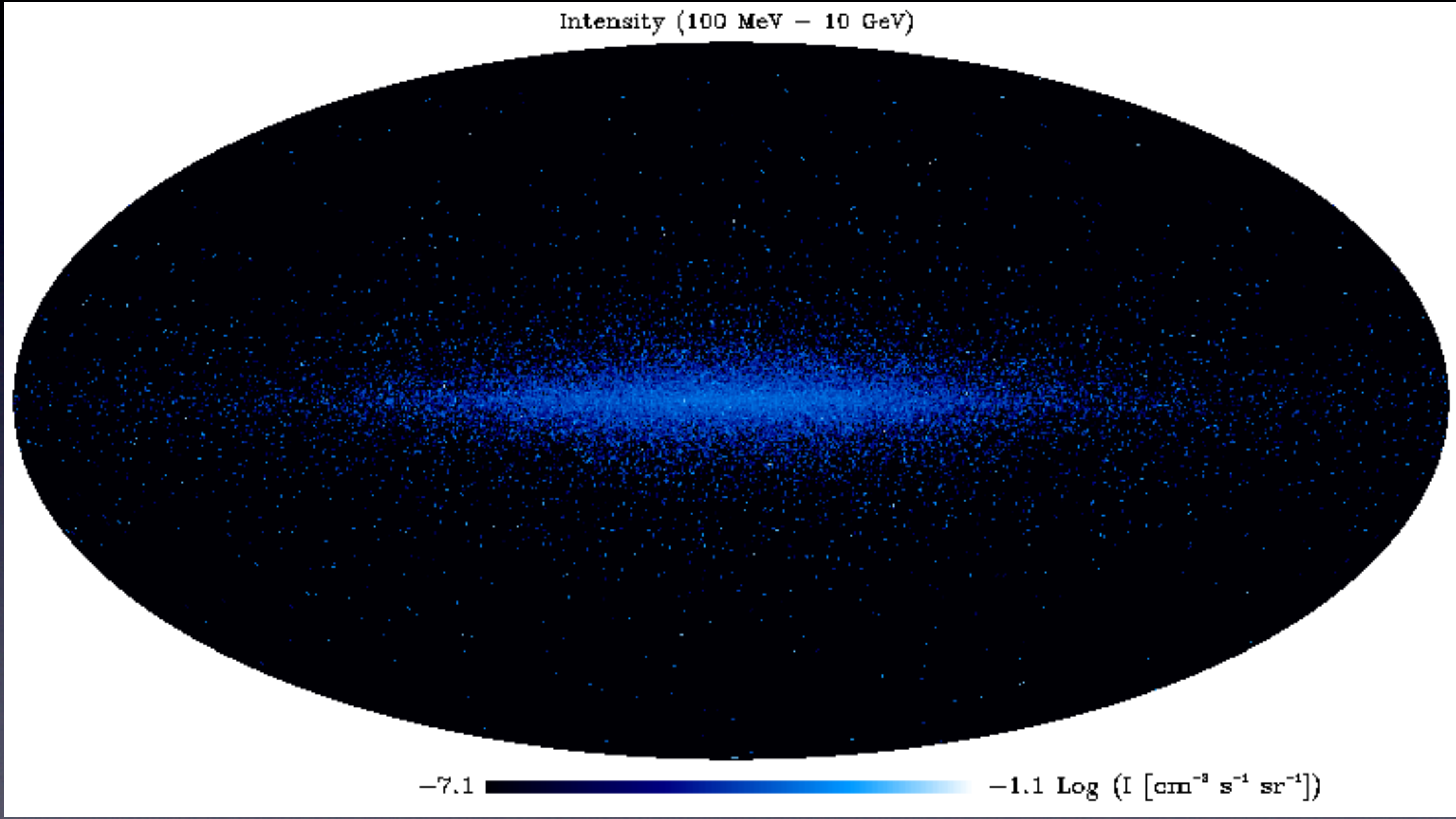
$$C_\ell^{\rm DM} = \frac{C_\ell^{\rm EG} C_\ell^{\rm tot}}{C_\ell^{\rm EG} - C_\ell^{\rm tot}}$$

Source spectra deconvolved!



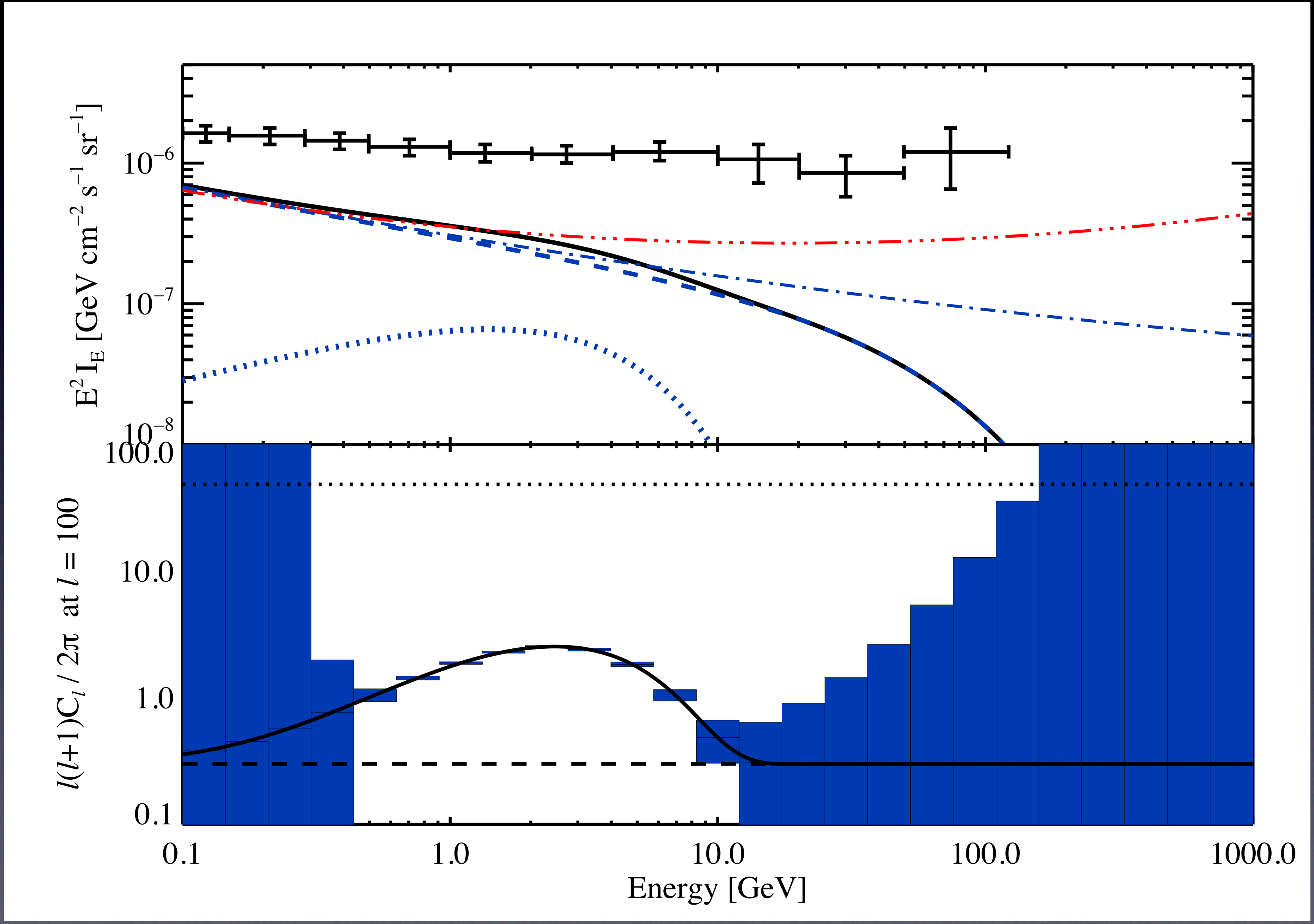
Hensley, Pavlidou & JSG (in prep)

Millisecond pulsar angular distribution



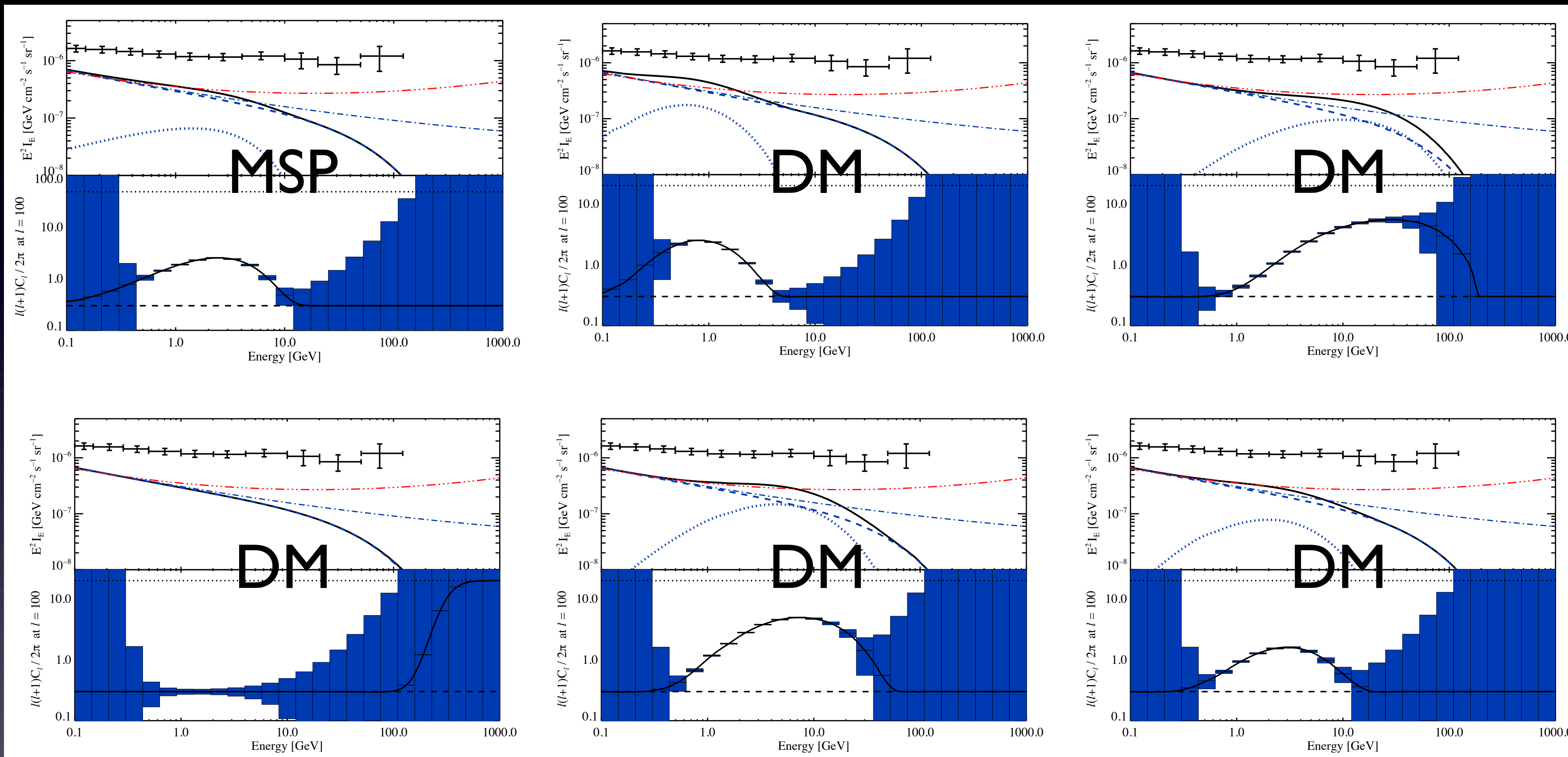
Pavlidou, Reesman, JSG, Profumo, & Walker (in prep)

MSP + blazar anisotropy energy spectrum



Pavlidou, Reesman, JSG, Profumo, & Walker (in prep)

Dark matter or MSPs?



Pavlidou, Reesman, JSG, Profumo, & Walker (in prep)

- due to typical cutoff in energy spectrum at 5 - 10 GeV, MSPs could mimic low-mass dark matter candidates with soft spectra, but unlikely to mimic most typical dark matter candidates
- MSPs may produce significant anisotropy → their diffuse contribution may be detectable/constrainable from Fermi data

Summary

- a modulation in the anisotropy energy spectrum robustly indicates a transition in energy in the spatial distribution of contributing source population(s)
- combining anisotropy and energy information can enable the detection of unresolved source populations that are subdominant in the intensity, such as dark matter, without requiring a firm prediction for the expected signal
- the anisotropy energy spectrum is sensitive to a large parameter space of dark matter models, and could extend the reach of current indirect dark matter searches
- the anisotropy energy spectrum could in principle be used to extract the shape of the dark matter intensity spectrum even if the dark matter contribution cannot be disentangled from the the intensity spectrum alone
- deconvolution could provide a model-independent way to extract the collective blazar energy spectrum
- these techniques are applicable to astrophysical source populations as well!